

## RMN

### UN PO' DI STORIA

#### Nuclear Magnetic Resonance



*Isidor Rabi*



*Felix Bloch*



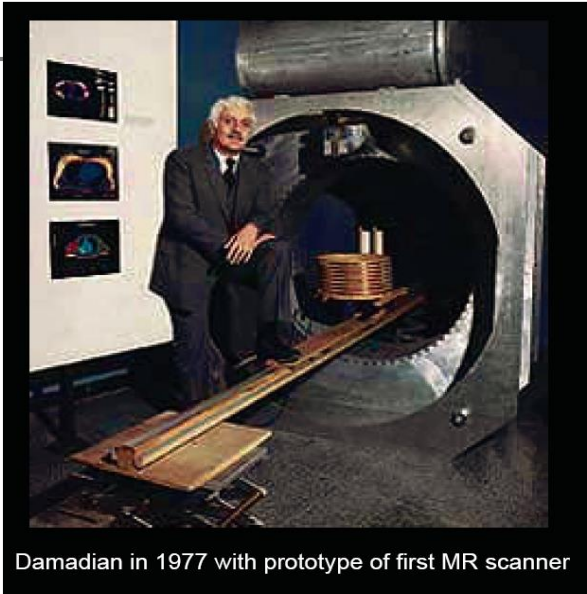
*Edward Purcell*

**nuclear:** properties of nuclei of atoms

**magnetic:** magnetic field

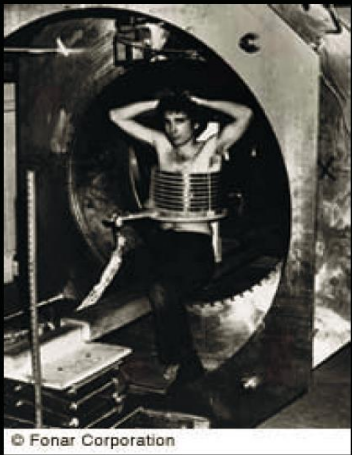
**resonance:** interaction between oscillating magnetic fields and atomic nuclei

Rabi (1944) and Bloch & Purcell (1952) win Nobel prizes for their contributions to NMR

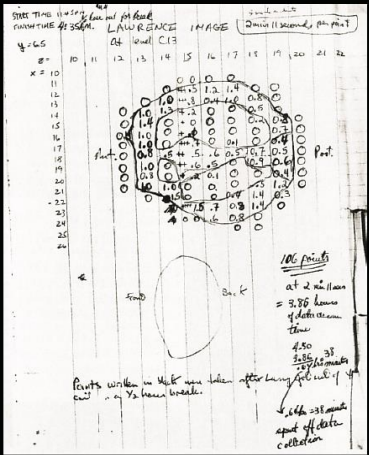


Damadian in 1977 with prototype of first MR scanner

# First Human MR Image



Damadian's postdoc, Larry Minkoff



Source: Huettel et al. slides

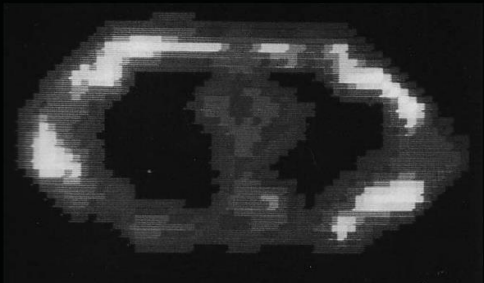
- 0.05T, only homogeneous in small volume at centre
- sampled image one voxel at a time, 2+ min/voxel \* 106 voxels = 4 hours!

Source: Jody Culham's fMRI for Dummies web site



# First Human MR Image

*Human Magnet 11:03 PM 7/1/77*  
*X = 18, Y = 2, Z = 6K*  
*Plane at 3 1/4" from bottom surface of*  
*head to magnet power surface*  
**FANTASTIC SUCCESS!**  
4:45 AM *First Human Image*  
*Complete in Amazing Detail*  
*Showing Heart*  
*Spine*  
*Vertebrae*  
*Musculature*



Source: Huettel et al. slides

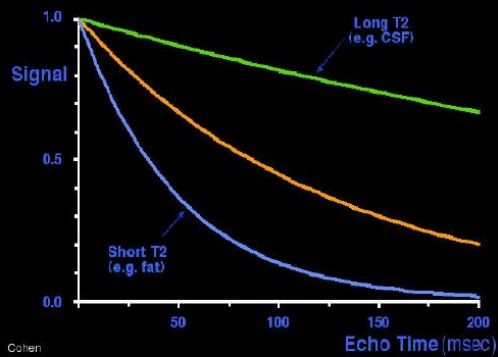
BLOCH.EXE

## T2 and TE

**T2** = decay of transverse magnetization

**TE** (time to echo) = time to wait to measure T2

### T2 and TE



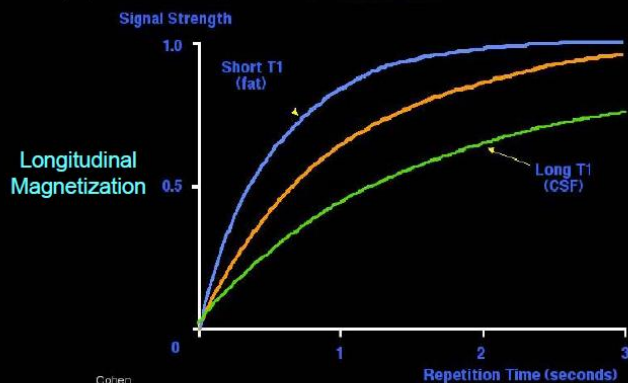
Source: [Mark Cohen's web slides](#)

## T1 and TR

**T1** = recovery of longitudinal ( $B_0$ ) magnetization

- used in anatomical images
- ~500-1000 msec (longer with bigger  $B_0$ )

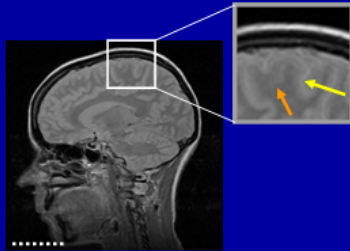
**TR** (repetition time) = time to wait after excitation before sampling T1



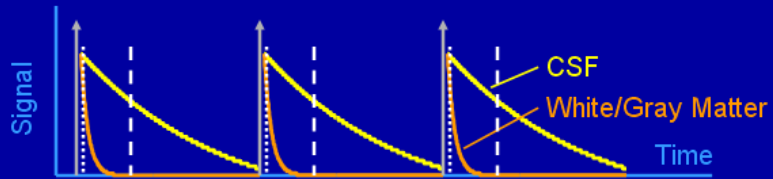
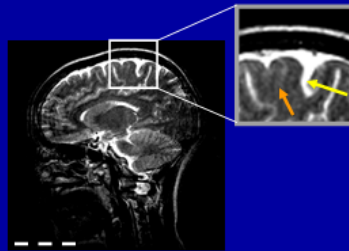
Source: [Mark Cohen's web slides](#)

## $T_2$ Contrast

Short Echo-Time



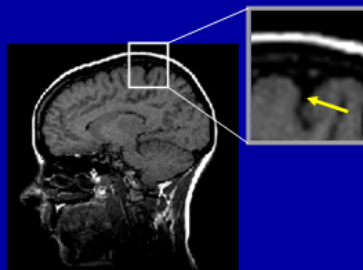
Long Echo-Time



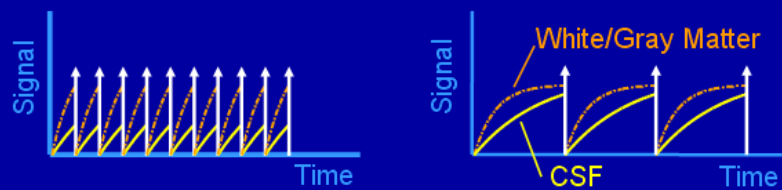
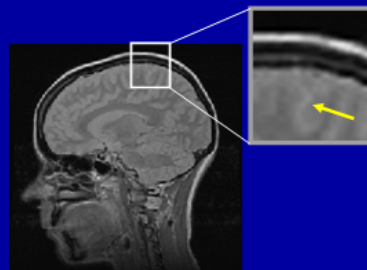
30

## $T_1$ Contrast

Short Repetition

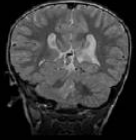

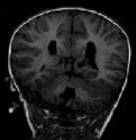


Long Repetition

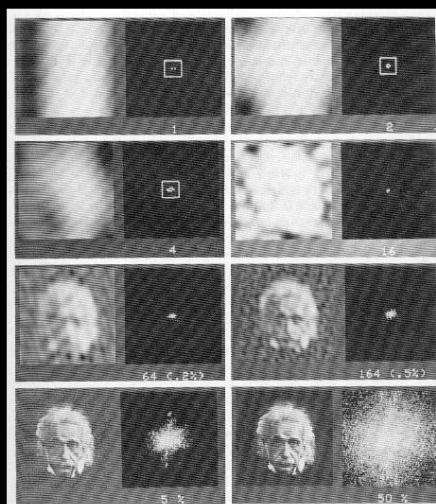


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## Image Weighting

		TE	
		Short	Long
TR	Long	 PROTON DENSITY	 T2-WEIGHTED
	Short	 T1-WEIGHTED	

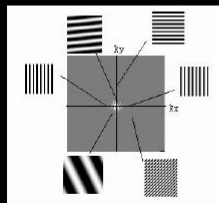
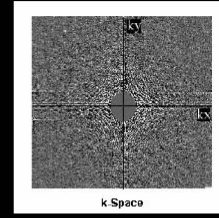
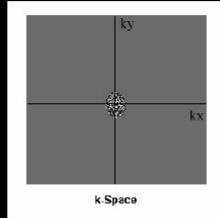
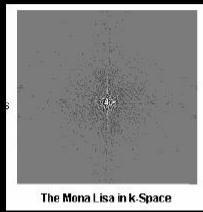
## Fourier Synthesis



- centre = low frequencies
- periphery = high frequencies
- You can see how the image quality grows as we add more frequency information

Source: DeValois & DeValois, *Spatial Vision*, 1990

## K-Space

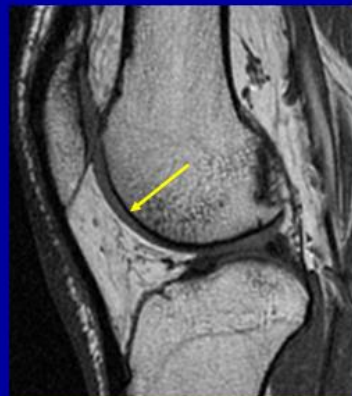


## Image Noise and SNR

Low Signal-to-Noise Ratio



High Signal-to-Noise Ratio



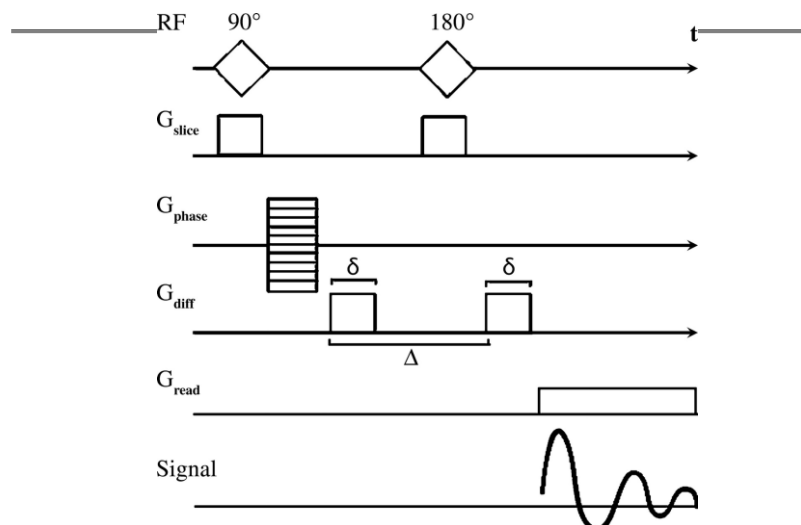


## Diffusion MRI

### Diffusion-weighted imaging (DWI)

- Confrontata con la classica spin eco la sequenza spin eco a gradiente impulsato che si usa per la diffusion MRI include due ulteriori gradienti di campo magnetico
- Per effetto del primo gradiente, i protoni in un pixel varieranno la loro velocità angolare di un fattore che dipende dal valore del campo magnetico in quel pixel. Questa variazione di velocità darà luogo ad una perdita di coerenza.
- In seguito è applicato un altro gradiente nella stessa direzione ma di ampiezza opposta il quale tenderebbe a rifocalizzare (rifasare) gli spin.
- Tuttavia la rifocalizzazione non sarà perfetta perché, alcuni protoni (molecole d'acqua) hanno abbandonato, per diffusione, il voxel nel tempo che intercorre tra i due impulsi. Quindi il segnale misurato dalla macchina MRI sarà ridotto.

Figure 9. Diagram shows the pulsed gradient SE sequence used for diffusion MR imaging.



Hagmann P et al. Radiographics 2006;26:S205-S223

RadioGraphics

©2006 by Radiological Society of North America



- La riduzione del segnale può essere correlata alla diffusione con un'equazione del tipo:

$$\frac{S}{S_0} = \exp(-bD)$$

- Dove  $S_0$  è l'intensità del segnale senza i gradienti di diffusione,  $S$  è il segnale in presenza dei gradienti,  $D$  è il coefficiente di diffusione e  $b$  un parametro proporzionale al ritardo  $\Delta$  tra due impulsi.
- Maggiore è  $b$  maggiore è il decremento del segnale.  $D$  viene estrapolato effettuando più misure con diversi  $b$  (diversi  $\Delta$ ).

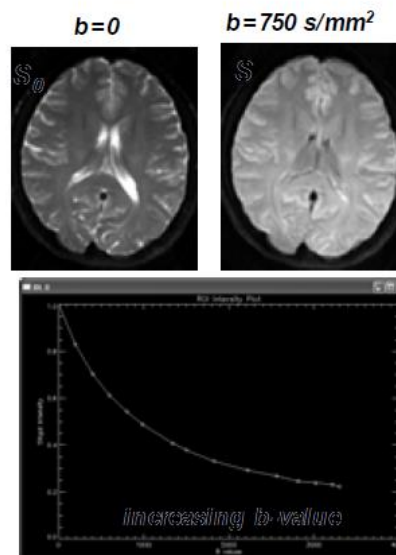
## ***b-value vs. Signal***

- *MRI signals are sensitive to diffusion*

$$S = S_0 \exp(-bD)$$

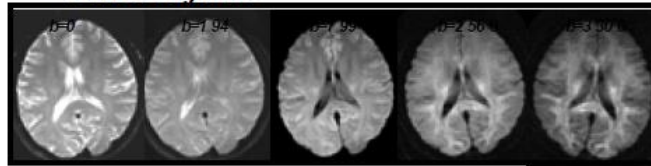
*b: b-factor*

*D: diffusion coefficient*



## *Impact of $b$ -value*

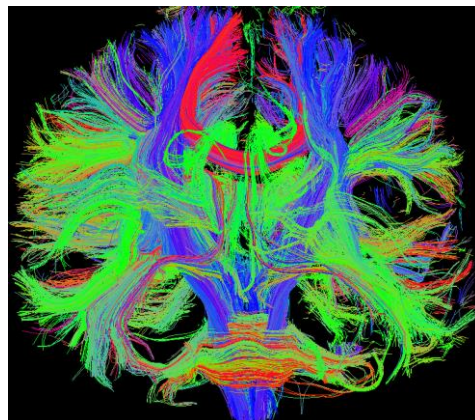
- *For high  $b$ -value*
  - *better diffusion contrast*
- *For low  $b$ -value*
  - *better SNR*
  - *shorter TE*
  - *less artifacts*



- *For most clinical use,  $b = 750-1000 \text{ s/mm}^2$*

## Human brain diffusion mapping

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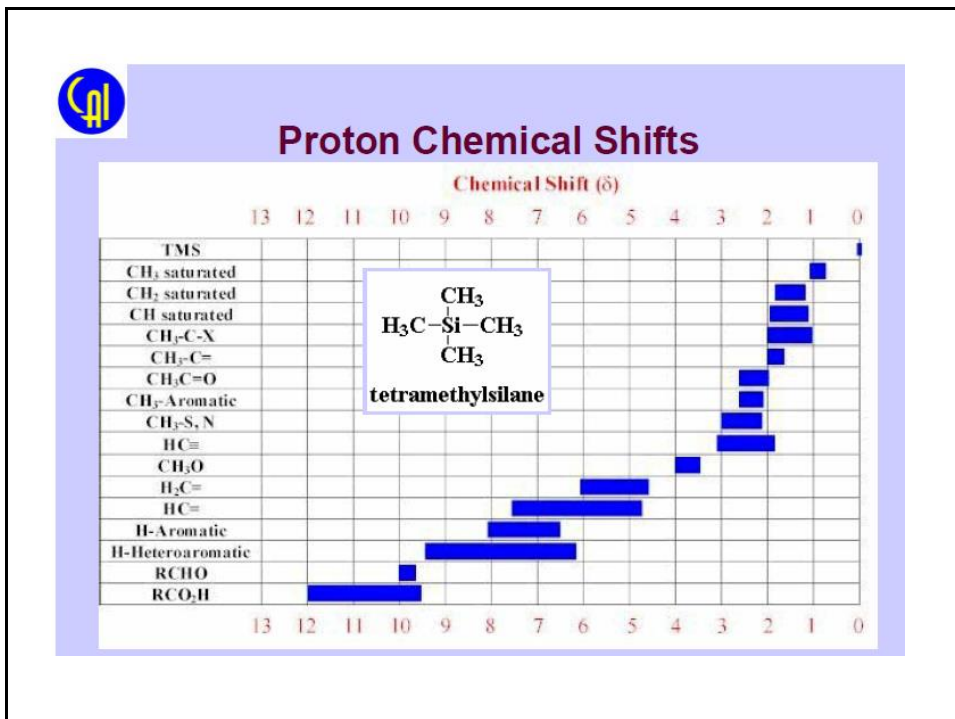
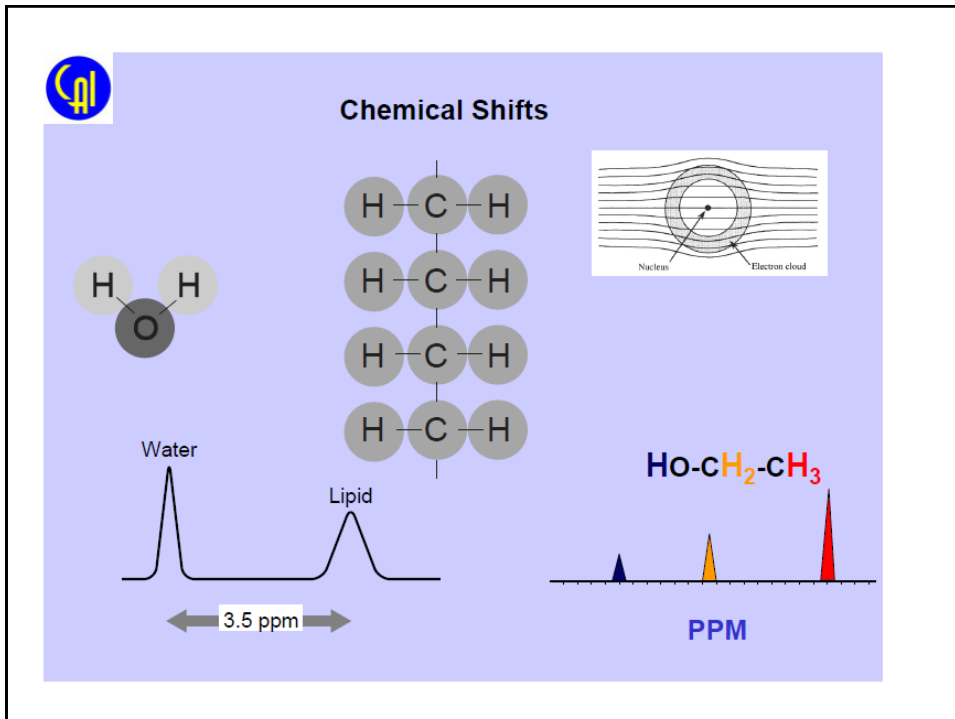


## Nuclear magnetic resonance spectroscopy MRS

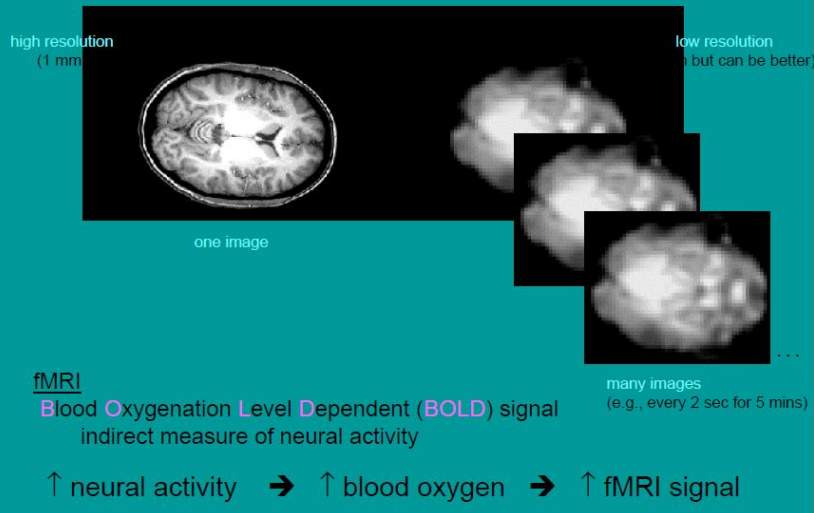
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- I diversi protoni di una molecola possono risonare a frequenze leggermente diverse in funzione dell'ambiente chimico locale.
- Poiché sia lo shift in frequenza che la frequenza di risonanza fondamentale sono direttamente proporzionali all'intensità del campo magnetico lo shift è convertito in un parametro adimensionale noto come chemical shift.
- il chemical shift è riportato come una misura relativa rispetto ad una assegnata frequenza di risonanza. In particolare, il TMS (tetramethylsilane) è comunemente utilizzato come riferimento.
- Il chemical shift è ottenuto facendo la differenza fra la frequenza di risonanza dell'elemento e la frequenza del riferimento e dividendo il risultato per la frequenza del riferimento

- 
- Gli shift che si ottengono sono estremamente piccoli rispetto alla fondamentale frequenza della RMN. Un tipico shift in frequenza è dell'ordine dei 100 Hz confrontato con una frequenza fondamentale di 64 MHz
  - Per questo motivo lo shift chimico è generalmente espresso in parti per milione (ppm).
  - Per poter rilevare differenze così piccole il campo magnetico applicato deve essere estremamente costante su tutto il volume del campione. A tal fine spesso si usano delle ulteriori bobine dette shims per migliorare l'omogeneità del campo.

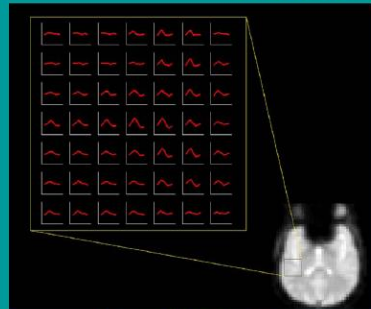


## MRI vs. fMRI

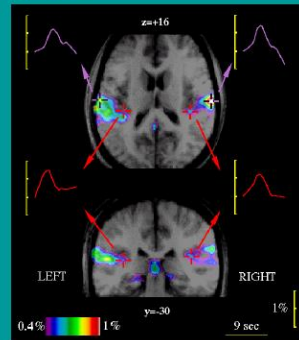


L'emoglobina de-ossigenata possiede infatti proprietà paramagnetiche, a differenza dell'emoglobina ossigenata. L'aumento di concentrazione di deossiemo globina provoca quindi cadute di segnale RM, la sua diminuzione causa un aumento di segnale, permettendo così di utilizzare l'emoglobina come mezzo di contrasto endogeno nello studio delle regioni cerebrali coinvolte dalla funzione studiata.

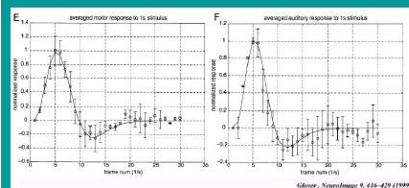
### Hemodynamic response



Belin et al. (1999) *Neuroimage*



- BOLD signal maximum 3-5 sec after sound onset
- returned to baseline 6-9 sec after sound onset

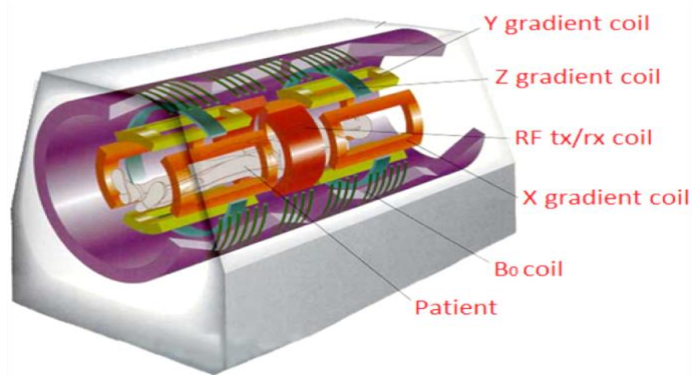


### Corso di Strumentazione Biomedica III

## ANTENNE

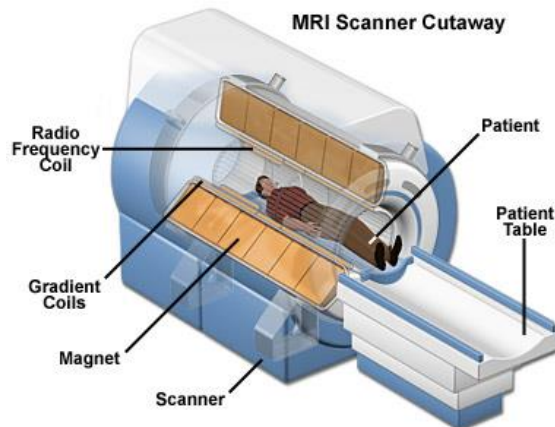
## NEI SISTEMI RMN

## MRI Tomograph



- MRI tomographs are composed of five coils: one for the main static magnetic field  $B_0$ , one for the RF transmission/reception, and three for the gradients

## MRI Funzionamento e Struttura





## *Bobine RF di superficie (coils)*

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## *Bobine RF locali*

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# A fast and accurate simulator for the design of birdcage coils in MRI

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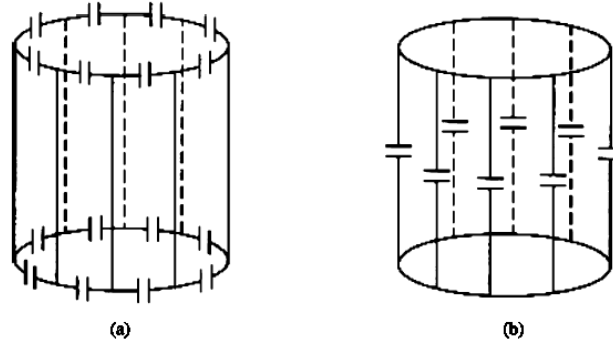


Fig. 1. (a) High-pass birdcage coil (b) Low-pass birdcage coil.

## BirdcageBuilder: Design of Specified-Geometry Birdcage Coils with Desired Current Pattern and Resonant Frequency

CHIH-LIANG CHIN,<sup>1</sup> CHRISTOPHER M. COLLINS,<sup>1</sup> SHIZHE LI,<sup>2</sup> BERNARD J. DARDZINSKI,<sup>3</sup> MICHAEL B. SMITH<sup>1</sup>

<sup>1</sup> Center for NMR Research, Department of Radiology, Pennsylvania State University, College of Medicine, Hershey, Pennsylvania 17033

<sup>2</sup> KGC-Medical Advances Inc., Milwaukee, Wisconsin 53288

<sup>3</sup> Imaging Research Center, Children's Hospital Medical Center, Cincinnati, Ohio 45229

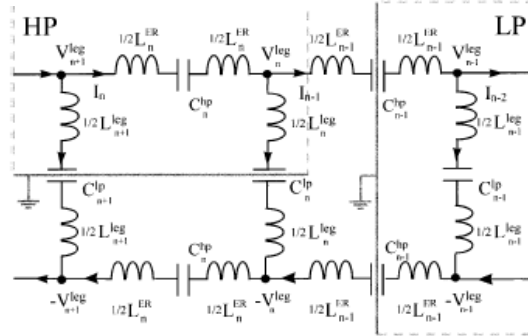
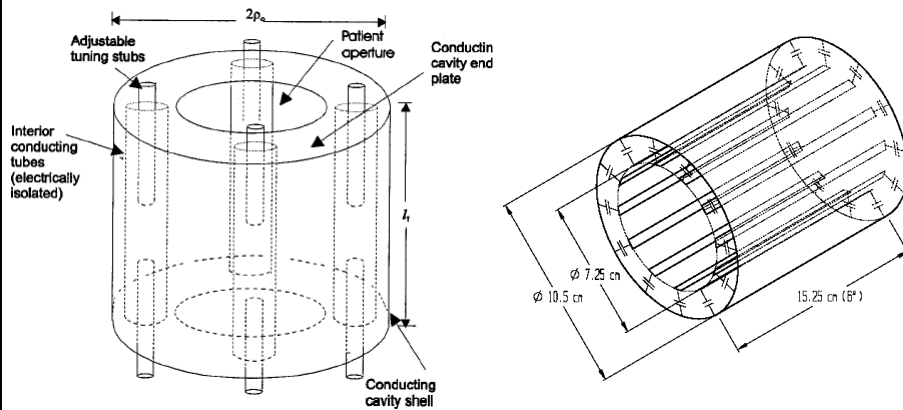
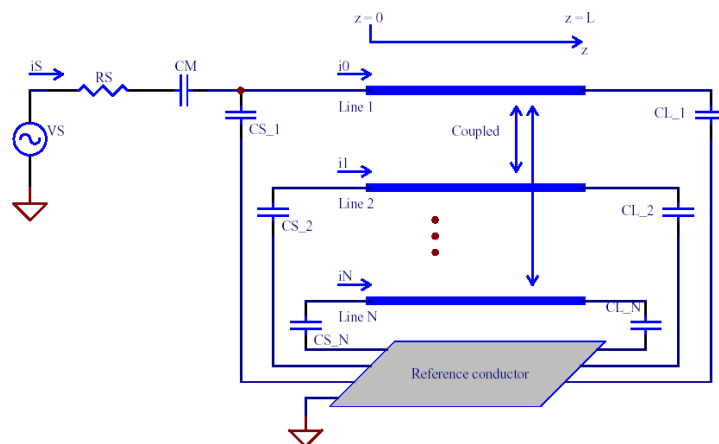


Figure 1 A circuit model for a band-pass birdcage coil design. The  $L_n^{\text{leg}}$  and  $L_n^{\text{ER}}$  are the effective inductances of the  $n$ th leg and ER segment, respectively;  $C_n^{\text{lp}}$  and  $C_n^{\text{hp}}$  are the capacitances on the  $n$ th leg and ER segment, respectively; and  $I_n$  is the current intensity in the  $n$ th loop. The voltage at the end point of the  $n$ th leg is  $V_n^{\text{leg}}$ . When  $C_n^{\text{lp}}$  is given, the virtual ground is assumed at the middle of the legs (see the left box labeled HP); if  $C_n^{\text{hp}}$  is known, a virtual ground is inserted at the middle of the  $(n - 1)$ th ER segments on both ER planes (see the right box labeled LP).

## TEM coils



## Modello per le TEM coils



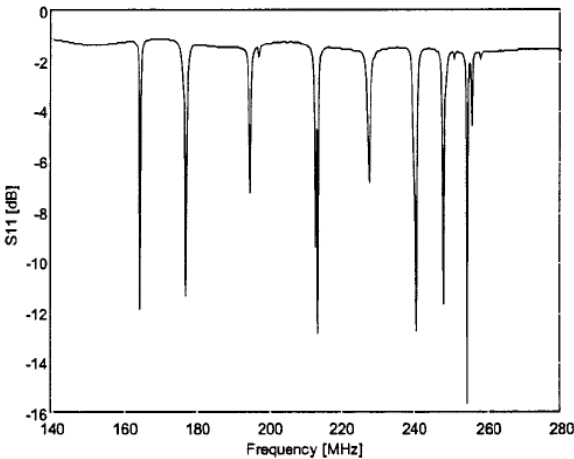
$$\frac{d}{dz} \underline{V} = - \underline{Z} \underline{I}$$

$$\frac{d}{dz} \underline{I} = - \underline{Y} \underline{V}$$

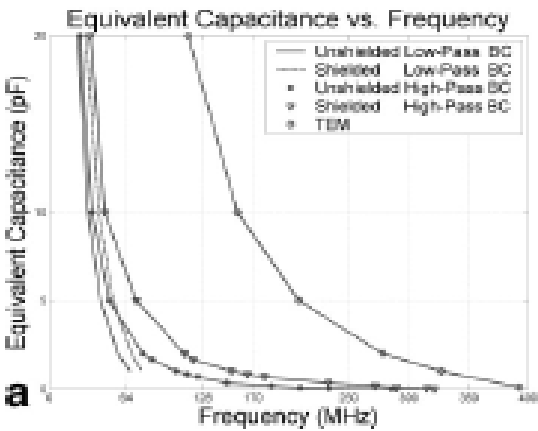
# Frequenze di risonanza

$$\prod_{n=1}^N (1 - \Gamma_n^+ \Gamma_n^- e^{-2\gamma l}) = 0$$

$$\omega_n = -j\gamma_n$$



# Confronto Birdcage-TEM



## Philips



Sistemi 1.5 T e 3 T



## Siemens



Sistemi  
1.5 T e 3 T

Sistemi 0.35 T



## General Electric (GE)



1.5 T e 3 T



Open  
0.2 T e 0.35 T

**esaote**

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**G-scan Brio**  
Un approccio RM rivoluzionario per tutte le applicazioni muscolo-scheletriche per diagnosi più precise e affidabili.



### O-scan

Ecco a voi il miglior sistema per RM degli arti: O-scan garantisce eccezionale qualità di immagine, imaging semplice e facilità di utilizzo, in linea con la tradizione Esaote.



### S-scan

Lo scanner RM dedicato S-scan rappresenta l'ultima evoluzione della tecnologia Esaote nell'ambito della tomografia RM.



## **Interazione RMN Portatori di pacemaker**

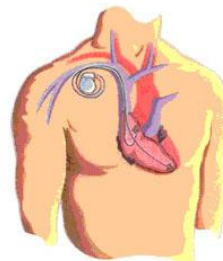
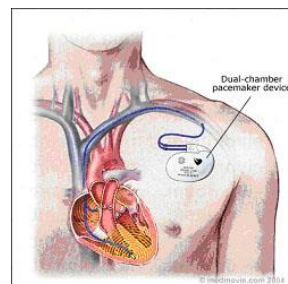


#Università degli Studi di Roma "La Sapienza"  
Dipartimento di Ingegneria Elettronica  
& Istituto Superiore di Sanità, Roma



Il pacemaker è costituito da un involucro in titanio e da un catetere che porta l'impulso elettrico al cuore passando attraverso il sistema venoso

Il pacemaker si applica a pazienti con patologie del tessuto cardiaco che ne abbiano compromesso la capacità spontanea a depolarizzarsi

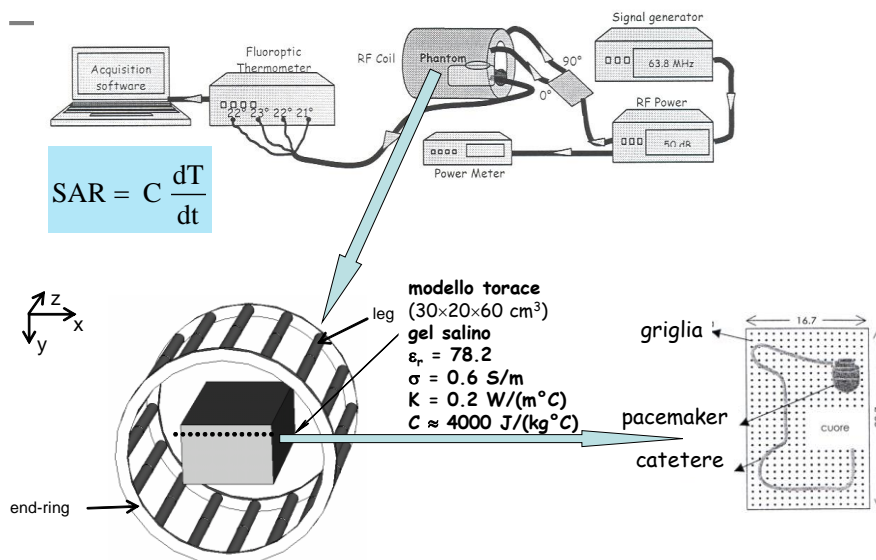


## ICNIRP Statement on: "Medical MR procedures: protection of patients" (2004)

In Italia la RMN è preclusa per legge ai portatori di pacemaker

- No adverse health effects are expected if the increase in body core temperature is less than  $1^{\circ}\text{C}$
- Adverse effects are avoided if temperatures in localized regions of the head remain lower than  $38^{\circ}\text{C}$  ( $\Delta T < 1^{\circ}\text{C}$ ), lower than  $39^{\circ}\text{C}$  in the trunk ( $\Delta T < 2^{\circ}\text{C}$ ), less than  $40^{\circ}\text{C}$  in the limbs ( $\Delta T < 3^{\circ}\text{C}$ )
- $\text{SAR}_{\text{WB}}$  should not exceed  $2 \text{ W/kg}$ , local SAR (averaged over  $10 \text{ g}$ ) is limited to  $20 \text{ W/kg}$  in the extremities and  $10 \text{ W/kg}$  in the head and trunk

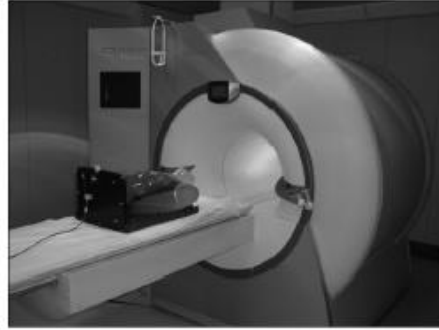
## Setup sperimentale ISS



## MRI Apparatus

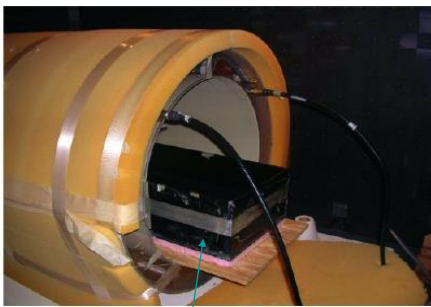


MRI apparatus:  
Birdcage Coil (64 MHz)  
ISS



MRI apparatus:  
Siemens Magnetom Sonata Maestro  
(1.5 T – 64 MHz)  
Mater Dei Hospital in Rome

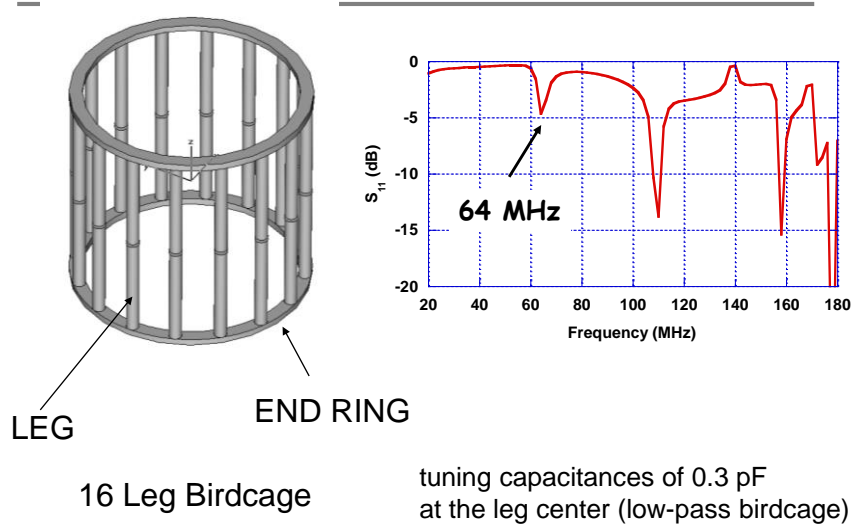
## Birdcage and Phantoms



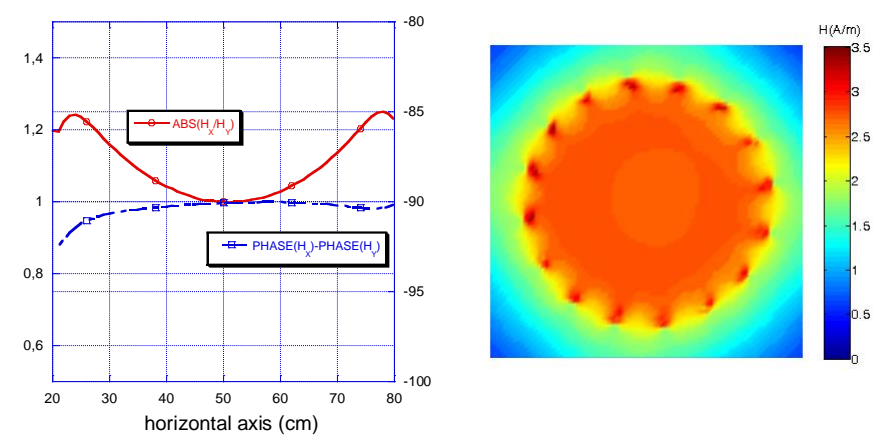
Physical phantom  
BOX ( $30 \times 20 \times 60 \text{ cm}^3$ ) gelled saline  
material  
Electric properties:  $\epsilon_r = 78.2$ ;  $\sigma = 0.6 \text{ S/m}$   
Thermal conductivity =  $0.2 \text{ W/(m}^\circ\text{C)}$   
Specific heat  $\approx 4000 \text{ J/(kg}^\circ\text{C)}$



# Birdcage Model



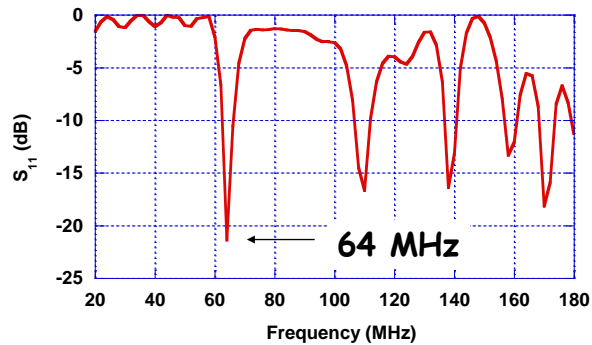
# Birdcage Magnetic Field



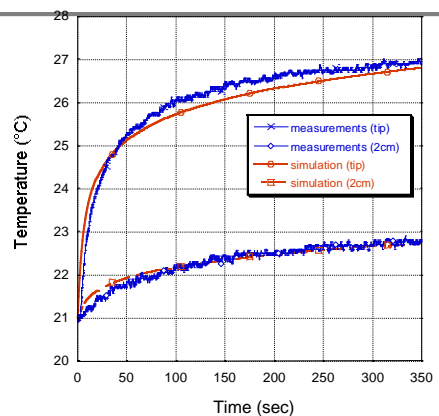
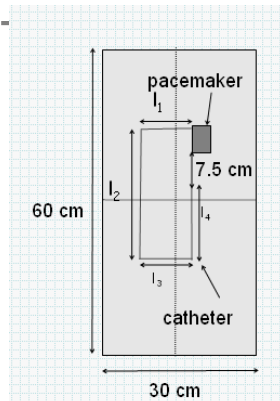
## Birdcage and Box Model of the Thorax

The thorax is modeled as a dielectric box  $30 \times 20 \times 60 \text{ cm}^3$

Electric constants  $\epsilon_r = 78.2$   $\sigma = 0.6 \text{ S/m}$



## Birdcage, Thorax and PM Model

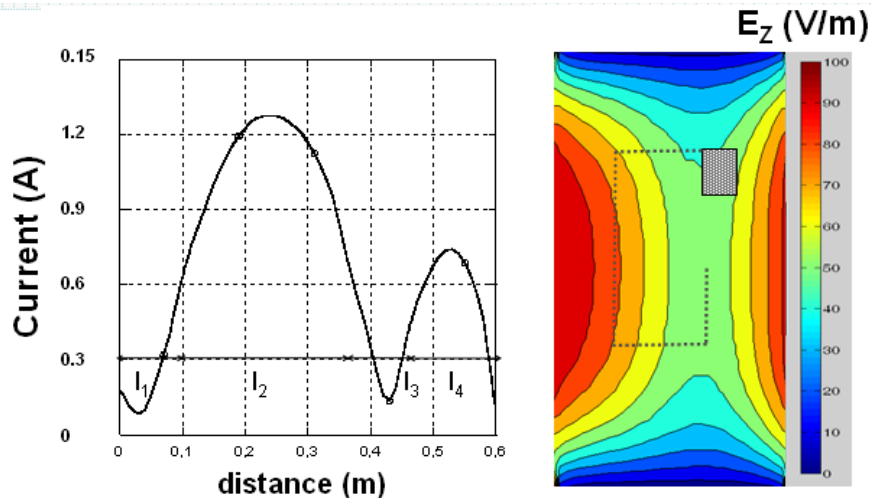


Section of the phantom model  
1 cm below the phantom surface

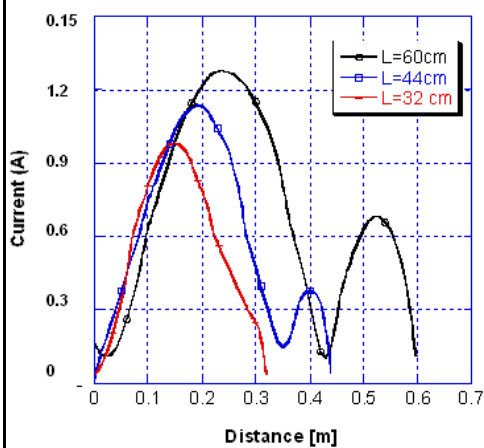
**Radiated power 100 W at 64 MHz ( $\text{SAR}_{\text{WB}} = 1 \text{ W/kg}$ )  $\text{SAR}_{\text{PEAK}} = 2400 \text{ W/kg}$**

S. Pisa, G. Calcagnini, M. Cavagnaro, E. Piuze, E. Mattei, and P. Bernardi, "A study of the interaction between implanted pacemakers and the radio-frequency field produced by magnetic resonance imaging apparatus", *IEEE Trans. Electromag. Compat.*, vol. 50, no. 1, pp. 35-42, February 2008.

## Current Along the Catheter



## Influence of the Catheter Length



$L = 60\text{ cm} \rightarrow \text{SAR}_{\text{PEAK}} = 2400\text{ W/kg}$

$L = 44\text{ cm} \rightarrow \text{SAR}_{\text{PEAK}} = 1400\text{ W/kg}$

$L = 32\text{ cm} \rightarrow \text{SAR}_{\text{PEAK}} = 1000\text{ W/kg}$

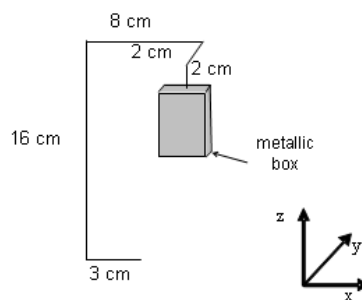
## "NPAC Visible Human Viewer"



- Applet Java che consente di visualizzare le immagini fotografiche delle sezioni
- Le immagini originarie (sezioni orizzontali) sono state elaborate per ottenere anche le sezioni verticali. Si hanno quindi a disposizione sezioni assiali, sagittali e coronali

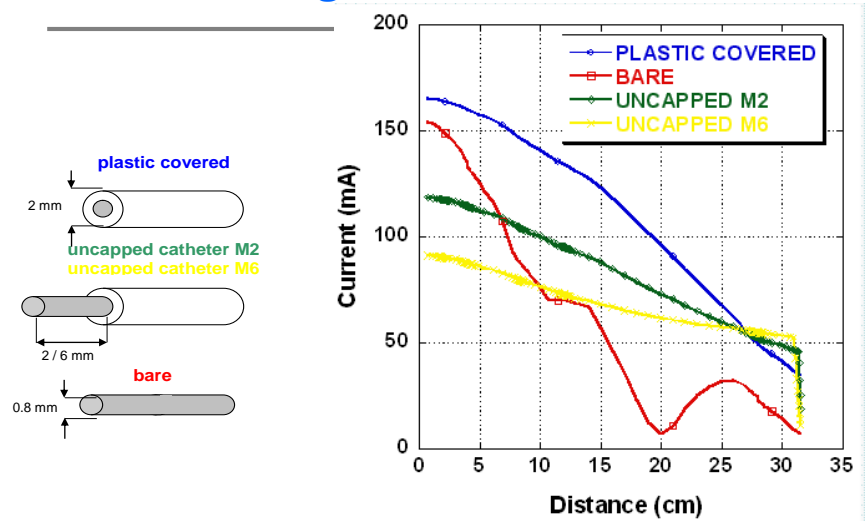
<http://rockefeller.univ-lyon1.fr/VisibleHumanProjectEnglish/VisibleHuman.html>

## Birdcage and VH Model of the Thorax





# Current Along the Catheter



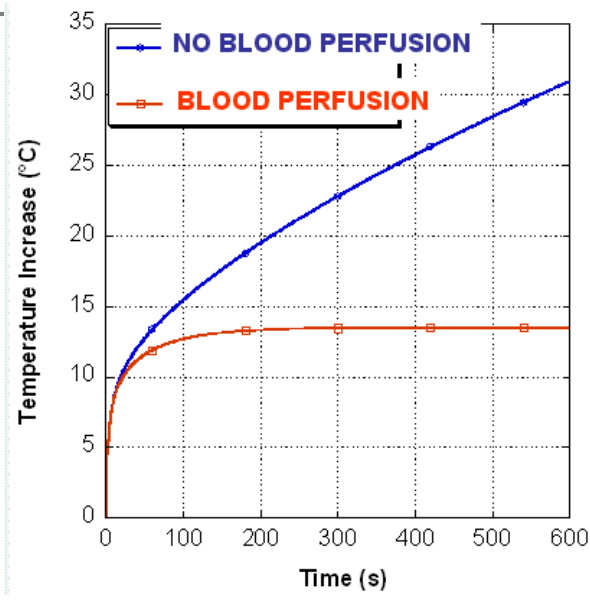
S. Pisa, P. Bernardi, M. Cavagnaro, and E. Piuze, "Power Absorption and Temperature Elevation Produced by Magnetic Resonance Apparatus in the Thorax of Patients With Implanted Pacemakers", *IEEE Trans. Electromag. Compat.*, vol. 54, no. 1, February 2010.

# SAR and Temperature Results

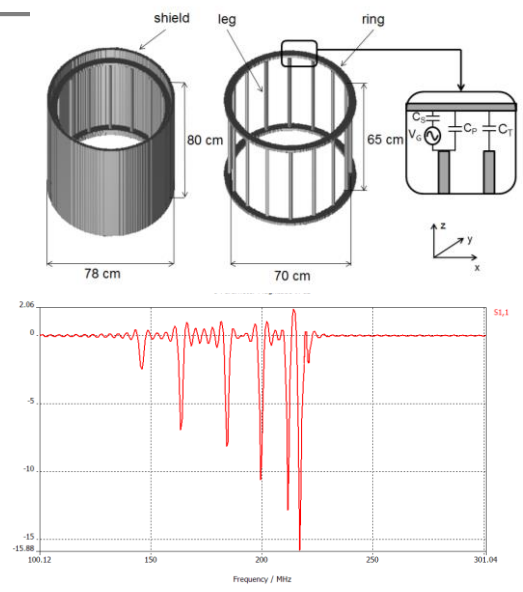
	Bare	UC-M6	UC-M2	PC
$SAR_1$ [W/kg]	15	700	2400	11900
$SAR_{10g}$ [W/kg]	5.6	5.6	7.9	9.8
$SAR_{WB}$ [W/kg]	0.5	0.5	0.5	0.5
Temp. Incr.* [°C]	0.2	1.9	5.8	13.5

\* After 10 min exposure and in the presence of blood perfusion

# Tempertaure at the Cateter Tip

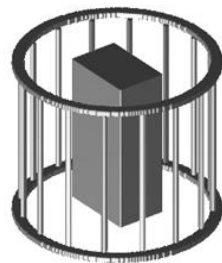
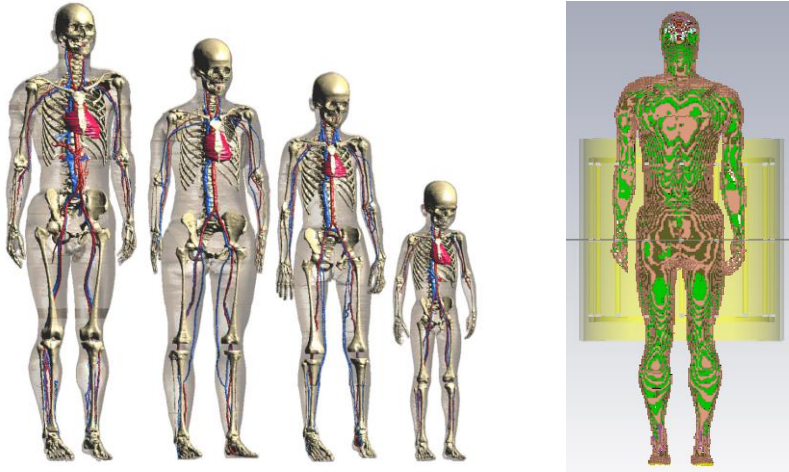


## TEM Coils



$N/2 + 1$   
resonances

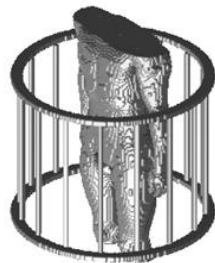
## Virtual family



(a)



(b)

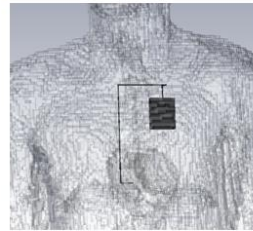
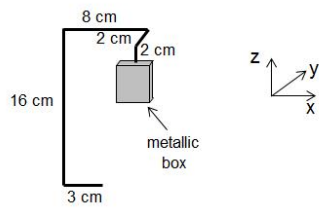


(c)



(d)

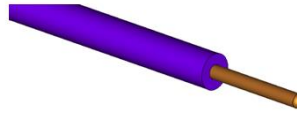
## PM Implanted Inside Duke



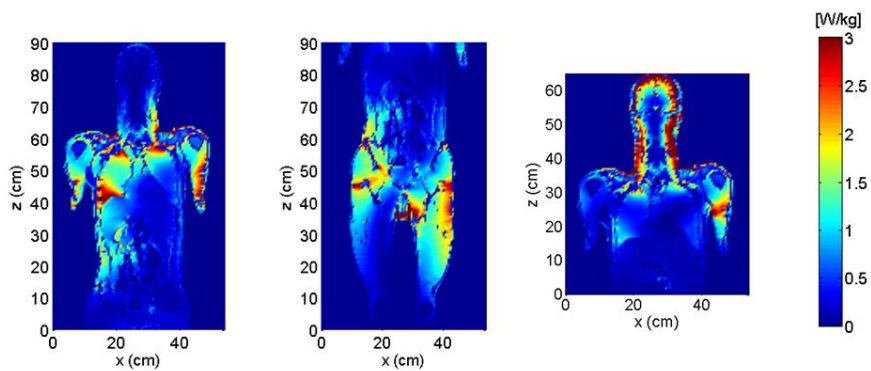
BARE



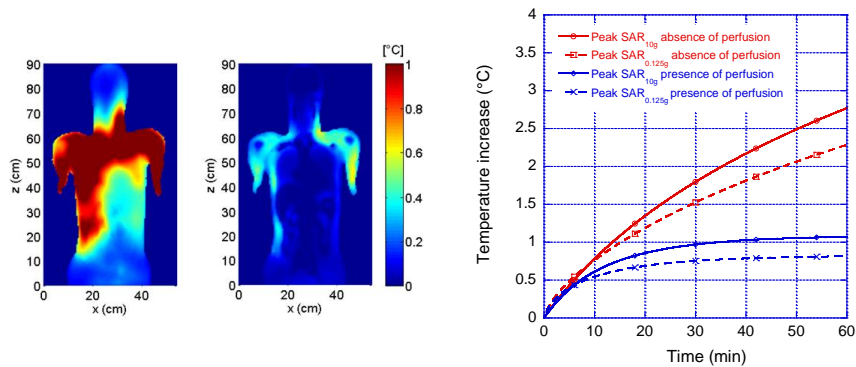
UC-6M



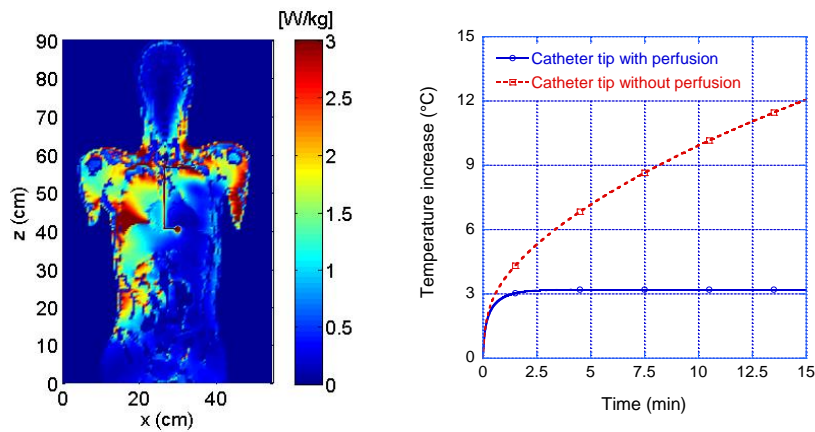
## SAR Distribution Inside Duke



# Temperature Distribution Inside Duke



# SAR Distribution Inside Duke with pacemaker



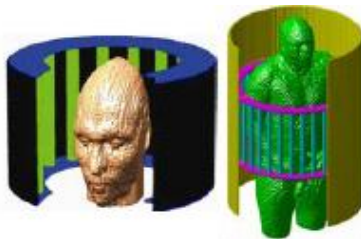
		3-T <sup>¶</sup> (128-MHz) <sup>¶</sup> TEM-Coil <sup>□</sup>	1.5-T <sup>¶</sup> (64-MHz) <sup>¶</sup> Birdcage-Coil <sup>□</sup>
BOX <sup>□</sup>	SAR <sub>WB</sub> <sup>□</sup>	1.0-W/kg <sup>□</sup>	1.0-W/kg <sup>□</sup>
// <sup>□</sup>	SAR <sub>10g</sub> <sup>□</sup>	3.4-W/kg <sup>□</sup>	2.9-W/kg <sup>□</sup>
// <sup>□</sup>	T <sub>MAX</sub> <sup>□</sup>	0.7-°C <sup>□</sup>	0.6-°C <sup>□</sup>
DUKE·THOR <sup>□</sup>	SAR <sub>WB</sub> <sup>□</sup>	0.49-W/kg <sup>□</sup>	0.46-W/kg <sup>□</sup>
// <sup>□</sup>	SAR <sub>10g</sub> <sup>□</sup>	4.7-W/kg <sup>□</sup>	4.4-W/kg <sup>□</sup>
// <sup>□</sup>	T <sub>MAX</sub> (WP) <sup>□</sup>	1.1-°C <sup>□</sup>	0.9 <sup>□</sup>
BOX+PM <sup>□</sup>	SAR <sub>WB</sub> <sup>□</sup>	1.0-W/kg <sup>□</sup>	1.0-W/kg <sup>□</sup>
// <sup>□</sup>	SAR <sub>10g</sub> <sup>□</sup>	16.6-W/kg <sup>□</sup>	17.1-W/kg <sup>□</sup>
// <sup>□</sup>	T <sub>MAX</sub> <sup>□</sup>	53-°C <sup>□</sup>	55-°C <sup>□</sup>
D·THOR+PM <sup>□</sup>	SAR <sub>WB</sub> <sup>□</sup>	0.49-W/kg <sup>□</sup>	0.46-W/kg <sup>□</sup>
// <sup>□</sup>	SAR <sub>10g</sub> <sup>□</sup>	5.5-W/kg <sup>□</sup>	14.0-W/kg <sup>□</sup>
// <sup>□</sup>	T <sub>MAX</sub> (WP) <sup>□</sup>	3-°C <sup>□</sup>	8.3-°C <sup>□</sup>

WP = with perfusion. T<sub>MAX</sub> are temperatures after 15 min exposure.

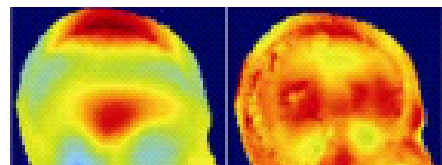
Tamer S. Ibrahim<sup>12</sup>, Roney Abraham<sup>2</sup>, Lin Tang<sup>2</sup>, and Doney Abraham<sup>2</sup>

<sup>1</sup>The University of Pittsburgh, Pittsburgh, Pennsylvania, USA

<sup>2</sup>The University of Oklahoma, Norman, Oklahoma, USA



9.4 Tesla  $\Rightarrow$  400 MHz



## Standard

ottimizzata

# SAR Evaluation of Pregnant Woman Models in 64 MHz MRI Birdcage Coil

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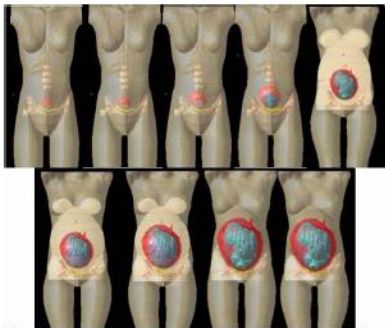


Fig. 3. Nine month pregnant woman models used in this investigation.

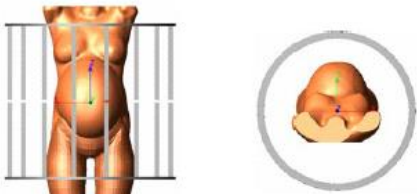


Fig. 4. Positioning of the 8 month model within the MRI RF coil.